Charmonia enhancement in quark-gluon plasma with improved description of c-quarks phase-distribution

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Abstract. We present a dynamical model of heavy quark evolution in the quark-gluon plasma (QGP) based on the Fokker-Planck equation. We then apply this model to the case of central ultra-relativistic nucleus-nucleus collisions performed at RHIC and estimate the component of J/ψ production (integrated and differential) stemming from c-$\bar{c}$ pairs that are initially uncorrelated.

1. Introduction

According to the first experimental results on open charm production in nucleon-nucleon reactions at RHIC ($\sqrt{s} = 200$ GeV), up to 40 c-$\bar{c}$ pairs could be formed in a central Au-Au collision at this energy. As noticed in [1], this large number could result in the formation of additional charmonia as compared to a simple scaling of nucleon-nucleon prompt production‖, due to c + $\bar{c}$ → ψ + X reactions happening later in the QGP. One would then observe a charmonia *enhancement* instead of suppression. However (i) D + $\bar{D}$ → ψ + X reactions happening during the ensuing hadronic phase can also contribute to charm enhancement and (ii) such an enhancement does not seem to be observed experimentally (preliminary J/ψ data appear to be compatible with the usual suppression). All of this indicates that the models should be refined. In fact, the actual distribution of c and $\bar{c}$ in phase-space could have a large impact on these recombination processes, but is often not treated with the care it deserves (or is simply beyond the scope of some models). Here, we will complement the model introduced in [1] by a dynamical treatment of the heavy-quarks evolution in the QGP based on a Fokker-Planck equation. We also present and discuss the differential spectra of c quarks and charmonia at the end of the QGP phase.

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‖ For a more detailed discussion of these ideas, see the contribution of R.L. Thews to this conference.

2. The model

Following [2, 3], the c and $\bar{\text{c}}$ quarks distributions in the QGP are assumed to follow a Fokker-Planck (FP) equation in momentum space.

$$\frac{\partial f(\vec{p}, t)}{\partial t} = \frac{\partial}{\partial p_i} \left[A_i(\vec{p}) f(\vec{p}, t) + \frac{\partial}{\partial p_j} \left(B_{ij}(\vec{p}) f(\vec{p}, t) \right) \right] \qquad (1)$$

The main justification for this hypothesis is that the heavy mass of these quarks implies large relaxation times as compared to the typical time of individual c + g → c′ + g′ and c + q → c′ + q′ collisions, whatever the momentum of the heavy quark. The drag (A) and diffusion (B) coefficients were evaluated according to [2, 3, 4], resorting to a power expansion "à la Kramers - Moyal" (KM) of the Boltzmann kernel of 2 → 2 collisions. As realized in [5], the asymptotic distribution coming out of the FP evolution deviates from a Boltzmannian. This results from the truncation of the KM series. We have therefore slightly corrected the B coefficients in order to guarantee a correct Boltzmannian asymptotic distribution. We have also checked on various examples that this modification has little effect at small evolution time. This constitutes our reference set of FP coefficients. In order to circumvent our lack of knowledge on the c-QGP interaction (radiative processes, non perturbative aspects, etc.¶), we will also consider alternative sets, obtained by multiplying the reference one by a numerical factor K. It is our hope that the gross experimental results will permit to fix an approximate value of K and that our model could then be used to predict finer aspects. In this respect, we view our model as a semi-predictive effective theory that could be useful to match the gap between the fundamental underlying theory (QCD) and experimental results.

The FP coefficients depend on position and time (only) through the local temperature and velocity of the surrounding medium, that is assumed to be locally thermalized and described via hydrodynamic evolution. Therefore, we do need to evaluate explicitly all microscopic c + g → c′ + g′ and c + q → c′ + q′ processes when performing our simulations: only c, $\bar{\text{c}}$ and J/ψ d.o.f. are considered.

For the sake of simplicity, we have neglected all initial state interactions in this exploratory work. We have also allowed ourselves to take a simple factorized form of the initial c − $\bar{\text{c}}$ phase-distribution, *i.e.* $f_{\text{in}}(\vec{r}_c, \vec{p}_c; \vec{r}_{\bar{c}}, \vec{p}_{\bar{c}}) \propto T_A(\vec{r}_{c,\perp}) T_B(\vec{r}_{\bar{c},\perp}) \delta^{(3)}(\vec{r}_c - \vec{r}_{\bar{c}}) \delta(z_c) \times f_{\text{in}}(\vec{p}_c) \times f_{\text{in}}(\vec{p}_{\bar{c}})$ with $f_{\text{in}}(\vec{p}_c) \propto f_{\text{in}}(\vec{p}_{c,\perp}) \times f_{\text{in}}(y_c)$, where $f_{\text{in}}(y_c)$ has been chosen according to [6] and $f_{\text{in}}(\vec{p}_{c,\perp})$ according to D transverse-momentum spectra at mid-rapidity in nucleon-nucleon reactions.

J/ψ mesons will be assumed to exist up to a dissociation temperature T_{diss} that we let as a free parameter. Under this temperature, they behave as if they were in vacuum. According to recent lattice calculation, T_{diss} could be substantially above the transition temperature. Apart from the prompt component, J/ψ are assumed to be formed and destroyed in the QGP via the c + $\bar{\text{c}}$ ↔ J/ψ + g processes [1]. In our simulation, these radiative dissociations are implemented via local dissociation rates that efficiently incorporate the microscopic processes.

¶ Ultimately, transport coefficients should be evaluated using lattice calculations.

3. Results and discussion

All results are for central Au+Au reactions at $\sqrt{s} = 200$ GeV. The initial number N_c of c and $\bar{c}$ quarks is taken to be 40, with $\frac{dN_c(y=0)}{dy} \approx 9$. Unless specified differently, the temperature and velocity profiles have been evaluated with the hydrodynamic model of Kolb and Heinz [7]. In order to address most clearly the effect of the uncorrelated J/ψ production, the prompt J/ψ component has been set to zero.
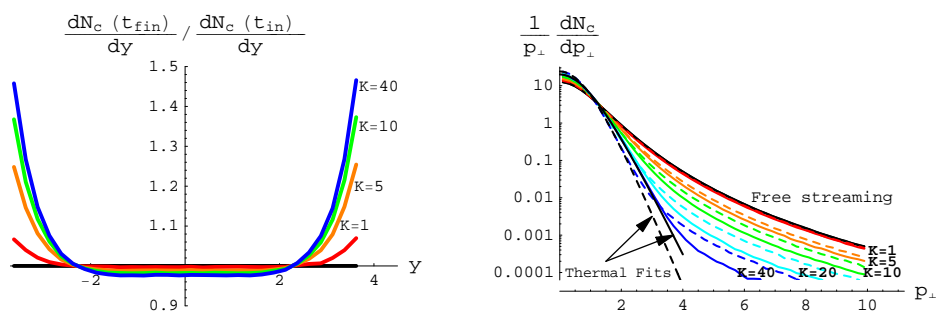
Figure 1. differential productions of c quarks at the end of the QGP phase: On the left panel, the rapidity distribution is presented relative to the one at initial time. On the right panel, transverse momentum spectra are displayed for Kolb and Heinz hydrodynamic evolution of QGP (full lines), as well as for some Bjorken hydrodynamic evolution with no transverse expansion (broken lines).

We show the differential productions profile of c quarks at the end of the QGP phase in figure 1 for different values of K. Let us remind that typical relaxation times are $\propto K^{-1}$. Thus, $K = 0$ corresponds to the free streaming case while $K \to +\infty$ corresponds to instantaneous equilibration of heavy quarks with the QGP.

On a broad window around mid-rapidity, the final profile deviates merely from the initial one. One just notices a small broadening for large values of K. Indeed, heavy quarks locate themselves very early in a slot of matter going at the same rapidity. The drag force thus vanishes and the heavy quarks conserve their rapidity for the rest of the evolution. However, diffusion processes can still happen and bring heavy quarks towards the tail of the rapidity distribution, leading to some rapidity broadening.

As for the transverse momentum distributions, the noticeable fact is the "cooling" of c quarks transverse motion by the QGP. One observes significant deviations from the free streaming case for $K \geq 5$ only. For large values of K, distributions tend to a Boltzmannian at small and intermediate values of $p_\perp$. As the distributions associated to different values of K interpolate smoothly between those two limiting cases, it might be possible – once initial and final state effects are included – to "read" the value of K from experimental spectra of D mesons.

We present the differential production of J/ψ at mid-rapidity on the left panel of figure 2. T_{diss} appears to have a much larger influence on this quantity than K. Once the initial number of c $-$ c̄ is fixed more accurately, it might be possible to assess the

value of $T_{\rm diss}$ and perform comparison with theoretical estimates. The right panel shows some typical predictions for J/ψ transverse spectrum at mid-rapidity. In all cases – but especially for large K – the prompt component is harder that the uncorrelated one.
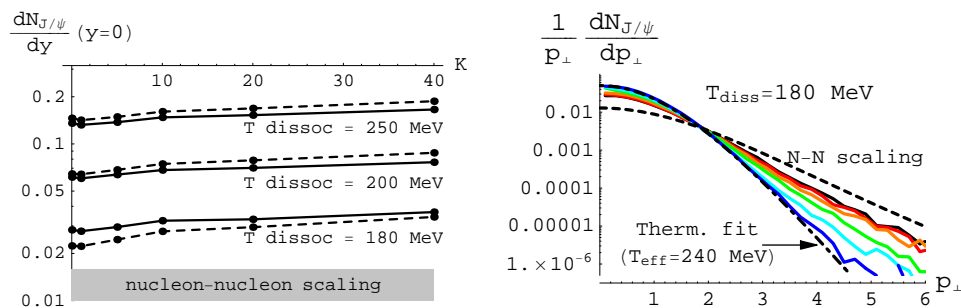
Figure 2. Left: J/ψ production at mid-rapidity at the end of the QGP phase with (full) and without (broken) radial expansion. Right: transverse momentum spectrum at mid-rapidity; plain lines correspond to $K = 0$ (hardest spectrum at large $p_\perp$), 1, 5, 10, 20 & 40. The chain curve represents the best fit of the $K = 40$ spectrum by a Boltzmannian, while the broken curve represents the prompt J/ψ component.

4. Conclusion and outlook

We have presented a model that copes efficiently with dynamical evolution of heavy quarks and quarkonia in QGP. We have evaluated J/ψ production at mid-rapidity as well as some differential spectra for different equilibration "strengths" K and for different dissociation temperatures. Hopefully, the comparison of such results with their experimental equivalent will ultimately allow to "measure" these parameters characteristic of the QGP phase.

Acknowledgments

References

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